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Ferromagnetic Single-Electron Transistor with RC Gate

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ABSTRACT

Ferromagnetic single-electron transistors coupled to the controlling gate potential by the gate resistance and gate capacitance in series are studied quantitatively. In this type of the device, several metastable charge states are possible within the Coulomb blockade range. The enhancement and hysteresis of tunnel magnetoresistance on drain and gate voltages are predicted. Inelastic macroscopic quantum tunneling of charge and existence of several charge states play an important role for the unique behavior of the tunnel magnetoresistance. This implies that RC-coupled ferromagnetic single-electron transistors have a new functionality as novel magnetoresistive nanostructure devices.

INTRODUCTION

Recent progress of nanotechnology to magnetic materials and magnetoresistive devices has attracted much attention. In ferromagnetic single-electron transistors (FMSETs), the interplay of the single-electron charging and spin-dependent tunneling effects is currently an attractive topic. In particular, the study of tunnel magnetoresistance (TMR) in FMSETs is a rapidly growing field. The proposal of single-electron transistors with capacitively and resistively coupled gates (C- and R-SETs) were first reported by Likharev in 1987 [1]. Since the structure of C-SET is easily realized experimentally, this has been studied in a great detail. In addition, capacitively coupled FMSETs (C-FMSETs) have also been investigated theoretically [2, 3] and experimentally [4-6]. In R-SETs, the gate resistance should be much larger than the quantum resistance to prevent quantum fluctuations of the island charge. Therefore, in contrast to C-SET, the R-SET is quite difficult to realize experimentally and has received practically no attention so far. However, theoretical and experimental studies on the R-SETs were presented recently [7, 8]. Moreover, electrical characteristics and TMR on resistively coupled FMSETs (R-FMSETs) have also been reported quantitatively in 2002 [9], but the R-FMSETs have not been studied experimentally.

In this paper, we propose another type of the FMSET, which is coupled to the controlling gate potential V_g by the gate resistance R_g and the gate capacitance C_g in series (RC-FMSETs). Since the current through the R_g may change the effective charge of the central electrode ("island") of the double junction system during the time interval between the tunneling events,

several metastable charge states are possible within the Coulomb blockade regime. Therefore, the potential of the island electrode and the drain current may exhibit hysteresis as a function of the gate potential. Considering the macroscopic quantum tunneling of charge (q-MQT) [10, 11], we study here transport properties of the electron in the RC-FMSET quantitatively.

MODEL

RC-coupled ferromagnetic single-electron transistor with double tunnel junction is shown in Fig. 1. The gate electrode consists of an RC circuit and connects an island electrode with the controlling gate potential. Source, drain and island electrodes are ferromagnetic metals. We assume that the magnetization in the electrodes usually shows the antiferromagnetic alignment in zero magnetic field (antiparallel configuration) and takes the ferromagnetic alignment with applying the magnetic field (parallel configuration). The polarization of source, drain and island electrodes can be taken into account by the difference between the tunnel resistances R_p (parallel) and R_{ap} (antiparallel) in each ferromagnetic tunnel junction. In other words, the tunnel resistance of each ferromagnetic tunnel junction is determined by the spin-dependent tunneling, which is R_p for the ferromagnetic alignment and R_{ap} for the antiferromagnetic alignment, and is treated as the junction resistance.

As mentioned above, the RC-FMSET has an $R_g C_g$ coupling circuit between the island and the gate potential. Hence, the relaxation time of the coupling circuit affects the effective background charge of the double junction system due to the variation of the charge at the coupling capacitance C_g . As a result, the charge state of the spin accumulation in the island may be influenced and released by a finite current going through the coupling circuit. In addition, the spin-flip relaxation time, which is crucial for the observation of the spin accumulation, strongly depends on the material quality of the island [12-15]. Therefore, we assume that the spin in the island is equilibrated [2, 3, 16, 17].

We consider the ferromagnetic tunnel junction system with the TMR = 20 % under the

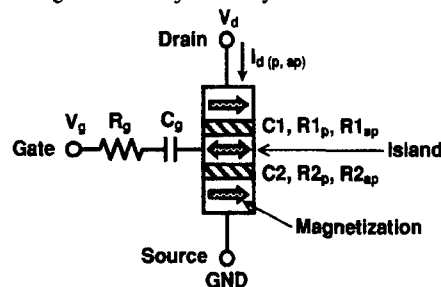


Figure 1. Schematic of an RC-coupled ferromagnetic single-electron transistor.

sequential tunneling regime, which corresponds to the spin polarization $P = 0.3$. So, if the tunnel resistances under the ferromagnetic alignment are assumed to $R_{1p} = 100 \text{ k}\Omega$ and $R_{2p} = 5 \times R_{1p} = 500 \text{ k}\Omega$, the tunnel resistances under the antiparallel configuration are given by $R_{1ap} = 1.2 \times R_{1p} = 120 \text{ k}\Omega$ and $R_{2ap} = 1.2 \times R_{2p} = 600 \text{ k}\Omega$. Capacitance of each ferromagnetic tunnel junction is also assumed to $C_1 = C_2 = 1 \text{ aF}$. The gate resistance R_g should be greater than the quantum resistance $R_Q = h/e^2$ and is set to $10 \text{ M}\Omega$ ($R_g \gg R_{1(p,ap)}, R_{2(p,ap)}$). The gate capacitance C_g is also given by $C_g/(C_1+C_2) = 3$. These parameters lead that the energy scale of the quantum fluctuations of the $R_g C_g$ coupling circuit $\hbar/(R_g C_t)$ (where $C_t = C_g(C_1 + C_2)/(C_1 + C_2 + C_g)$) is less than $e^2/(C_1 + C_2)$. This implies that for the typical current $I_{d(p,ap)} \sim e/((R_{1(p,ap)} + R_{2(p,ap)})(C_1 + C_2))$ the relaxation time of the $R_g C_g$ coupling circuit is greater than the typical time interval of the tunneling events $e/I_{d(p,ap)}$. The dynamics of the RC-FMSET can be calculated within the framework of the semiclassical model [18]. In the calculation, Monte Carlo procedure is used, and the rate of 2nd order inelastic q-MQT (co-tunneling) is also considered in addition to the rate of usual single-electron tunneling.

RESULTS AND DISCUSSION

Figure 2 shows drain currents for parallel and antiparallel configurations and TMR as a function of the drain voltage on the RC-FMSET. In this result, the temperature and the gate voltage are set at $T = 1 \text{ K}$ and $V_g = 0 \text{ V}$, respectively. Due to the large difference between $R_{1(a,ap)}$ and $R_{2(a,ap)}$, one can see the Coulomb staircases. Furthermore, the drain currents clearly show the hysteresis as a function of the drain voltage. Although the TMR shows 20 % when the Coulomb blockade is released as expected, the TMR is increased up to 44 % under the Coulomb blockade regime. This is due to the difference in the rate of the single-electron tunneling and the inelastic q-MQT. Moreover, hysteresis of the TMR is also observed, which is due to the hysteresis on the Coulomb blockade. This is a unique feature of the RC-FMSET in contrast to the usual C- and R-

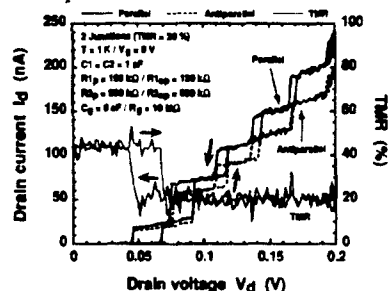


Figure 2. Drain currents and TMR ratio as a function of drain voltage on an RC-coupled ferromagnetic single-electron transistor.

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FMSETs. From the semiclassical model on the RC-FMSET, the charge injection from the $R_g C_g$ coupling circuit to the island electrode is determined by the potential $V_{RC} = V_g - V_d C_1 / (C_1 + C_2)$. Therefore, for the charge state with definite number n of excess electrons in the island electrode, charge Q_n on the equilibrium in the $R_g C_g$ coupling circuit is expressed as $Q_n = (ne + Q_0 + C_g V_{RC}) / (C_1 + C_2 + C_g)$, where Q_0 is the background charge of the island electrode. Since the condition of the blockade for the definite charge state n is given by $|Q_n| < e/2$, the charge Q_n shows the several metastable charge states satisfying the condition $|Q_n| < e/2$. The charge Q_n of the RC-FMSET implies that the addition of the electron to the island electrode causes the increase of the effective charge Q_n only by $e(C_1 + C_2) / (C_1 + C_2 + C_g)$, leading that several stable states are possible within the blockade. This is the origin of the hysteresis on the drain currents and the TMR. In this system, the stability threshold voltage for a certain charge state n is given by $V_{th}(n) = \min\{(e/2 - Q_n)C_1, (e/2 + Q_n)C_2\}$ ($V_{th}(n) > 0$) and can be varied by changing the gate potential. The maximum value becomes to $V_{th, \max} = e / (C_1 + C_2)$ from the condition $(e/2 - Q_n)C_1 = (e/2 + Q_n)C_2$. Its minimum value corresponds to the condition $V_{th}(n) = V_{th}(n+1)$ which gives $V_{th, \min} = e C_g / ((C_1 + C_2)(C_1 + C_2 + C_g))$. Hence, in RC-FMSET one can't suppress the threshold voltage to zero by varying the gate potential.

Figure 3 (a) shows the modulation characteristics of the drain current in a parallel configuration with different gate voltages. The gate voltages are varied from 0 mV (bottom) to 30 mV (top). Each curve is shifted vertically by 50 nA for clarity. One can see the periodic modulation of Coulomb blockade region by the variation of the gate voltage. Furthermore, hysteresis window of the drain current is also modified by the variation of the gate voltage. The relation between the TMR and the drain voltage at each gate voltage is illustrated in Fig. 3 (b). The TMR is clearly enhanced and defined to 44 % inside the Coulomb blockade. The modulation of the hysteresis window is clearly observed by varying the gate voltage.

Drain currents for parallel and antiparallel configurations and TMR as a function of the gate voltage are shown in Fig. 4. The temperature and the drain voltage are set at $T = 1$ K and $V_d = 50$ mV, respectively. The charge state of the device moves to the neighboring stable state when the

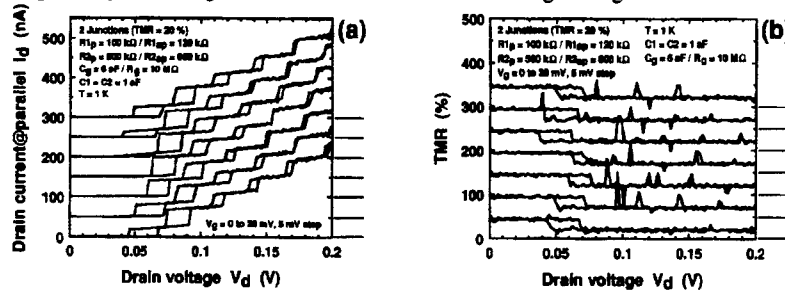


Figure 3. (a) Drain current and (b) TMR ratio as a function of drain voltage on an RC-coupled ferromagnetic single-electron transistor.

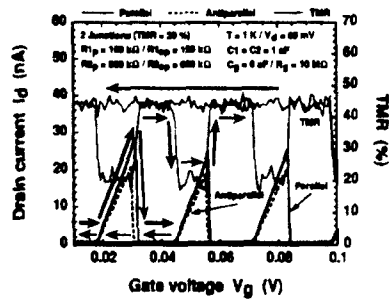


Figure 4. Drain currents and TMR ratio as a function of gate voltage on an RC-coupled ferromagnetic single-electron transistor.

gate voltage is increased. Thus the drain currents for a fixed drain voltage show a periodic function of the gate voltage with the period of e/C_g , which is similar to that of the C-FMSET. Then, as the gate voltage is decreased, the drain currents hardly show current flow, which is due to that the device is in the Coulomb blockade state. The behavior of the drain currents depending on the sweep direction of the gate voltage causes the hysteresis of the TMR as illustrated in Fig. 4. The TMR is increased up to 44 % within the Coulomb blockade range and is modulated between 20 % and 44 % depending on the behavior of the drain currents.

Figure 5 (a) shows the drain currents for parallel and antiparallel configurations at $T = 1$ K and $V_d = 50, 70$ and 90 mV as a function of the gate voltage. The curves are shifted vertically by 30 nA for clarity. As expected, the drain currents at the fixed gate voltage increase with increasing the drain voltage. Since the maximum threshold voltage of the Coulomb blockade becomes to $V_{th, max} = e/(C_1 + C_2) = 80$ mV in this device, the hysteresis of the drain currents becomes clear when the drain voltage is greater than the $V_{th, max}$. The potential of the island electrode V_{island} is defined as $V_{island} = (Q_n + V_d C_1)/(C_1 + C_2)$, therefore the V_{island} exhibits hysteresis due to the several charge states by the variation of the gate voltage, resulting in the hysteresis of the drain current on the gate voltage. The relation between the TMR and the gate

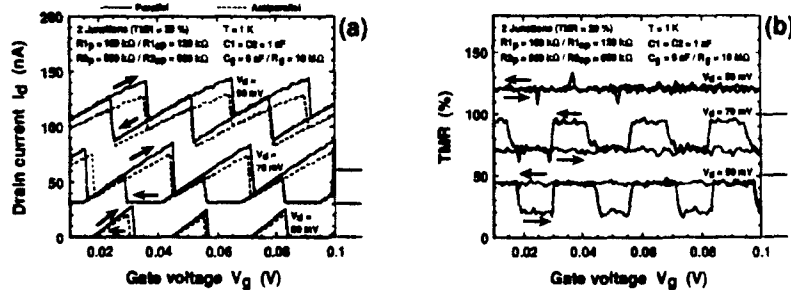


Figure 5. (a) Drain current and (b) TMR ratio as a function of gate voltage in different drain voltages.

voltage is shown in Fig. 5 (b). The curves are shifted vertically by 50 % for clarity. The TMR is 20 % at $V_d = 90$ mV, in which the bias condition is away from the blockade. In contrast, the TMR is successfully modulated within the blockade conditions ($V_d = 50$ and 70 mV), depending on the behavior of the drain currents. It should be noted that by using RC-FMSET, the enhancement and hysteresis of the TMR could be controlled by the drain and gate voltages.

CONCLUSIONS

In conclusion, we have proposed and studied ferromagnetic single-electron transistors controlled with RC gate. The inelastic q-MQT process under the Coulomb blockade regime leads to a considerable enhancement of TMR. Several metastable charge states within the Coulomb blockade range cause a clear hysteresis of TMR. These features have a specific dependence on the gate and drain voltages. This result implies a new functionality of the RC-FMSET.

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